

LIQUID CHROMATOGRAPH PUMP AND CONTROL METHOD THEREFOR

## Background of the Invention

The present invention relates to a pump for feeding a liquid for chromatography and a control method therefor.

5           In a prior art pump as disclosed JP-U-63-36668, when a first plunger move to put a liquid into the pump, a second plunger move to feed the liquid out of the pump so that a change in flow rate of the liquid discharged from the pump is decreased.

## 10   Brief Summary of the Invention

          An object of the present invention is to provide a pump for feeding a liquid for chromatography and a control method therefor, by which pump and method a minimal flow rate of the liquid is correctly  
15   maintained without a discontinuation of the correctly maintained minimal flow rate of the liquid.

          In a pump for feeding a liquid for chromatography, comprising first and second chambers, first and second plungers forming first and second  
20   volumes respectively together with the first and second chambers and being capable of reciprocating in the first and second chambers respectively in such a manner that the first and second volumes are variable in accordance with respective movements of the first and

second plungers, a communication path connecting fluidly the first and second volumes to each other, an inlet path communicating fluidly with the first volume, from which inlet path the liquid to be fed is capable  
5 of being supplied into the first volume, and an outlet path communicating fluidly with the second volume, by which outlet path the liquid to be fed is capable of being discharged from the second volume, according to the present invention, the first plunger is prevented  
10 from changing the first volume sufficiently for feeding the liquid between the first volume and the second volume when the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the chromatography.

15           Since the first plunger is prevented from changing the first volume sufficiently for feeding the liquid between the first volume and the second volume when the second plunger decreases the second volume to discharge the fluid from the second volume to the  
20 outlet path for the chromatography, the minimal flow rate of the liquid is correctly maintained without the discontinuation of the correctly maintained minimal flow rate of the liquid.

          It is further preferable for correctly  
25 maintaining the minimal flow rate of the liquid without the discontinuation of the correctly maintained minimal flow rate of the liquid that the first plunger is prevented from changing the first volume sufficiently

for changing a pressure of the liquid in the second volume through the communication path when the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the chromatography.

It is preferable for correctly keeping the pressure in the second chamber stably constant that the communication path connects fluidly the first and second volumes to each other in series so that the liquid to be fed for the chromatography is capable of being fed from the first volume through the communication path to the second volume, the communication path includes a check valve for allowing the liquid to flow from the first volume into the second volume when a pressure in the first volume is higher than a pressure in the second volume and preventing the liquid from flowing from the second volume into the first volume when the pressure in the first volume is not higher than the pressure in the second volume. It is preferable for restraining the discontinuation of the correctly maintained minimal flow rate of the liquid caused by the first plunger movement for decreasing the first volume to compensate the second plunger return movement increasing the second volume that when the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the chromatography, the first plunger is capable of decreasing the first volume to increase the pressure of

the liquid in the first volume to more than a pressure in the inlet path (at an upstream side of a check valve in the inlet path) and is prevented from decreasing the first volume sufficiently for increasing the pressure of the liquid in the first volume to more than the pressure in the second chamber. The check valve may allow the liquid to flow from the first volume into the second volume when the pressure in the first volume is more than the pressure in the second volume and a difference in absolute value between the pressure in the first volume and the pressure in the second volume is more than a predetermined value more than zero, and prevent the liquid from flowing from the first volume into the second volume when the pressure in the first volume is not more than a total amount of the pressure in the second volume and the predetermined value. It is preferable for restraining the discontinuation of the correctly maintained minimal flow rate of the liquid caused by the first plunger movement for decreasing the first volume to compensate the second plunger return movement increasing the second volume that the first plunger is prevented from decreasing the first volume sufficiently for increasing the pressure of the liquid in the first volume to more than the total amount of the pressure in the second volume and the predetermined value when the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the

chromatography. It is preferable for restraining the discontinuation of the correctly maintained minimal flow rate of the liquid caused by the first plunger movement for decreasing the first volume to compensate  
5 the second plunger return movement increasing the second volume that when the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the chromatography, the first plunger is capable of decreasing the  
10 first volume to increase the pressure of the liquid in the first volume to more than a pressure in the inlet path (at an upstream side of a check valve in the inlet path) and is prevented from decreasing the first volume sufficiently for increasing the pressure of the liquid  
15 in the first volume to more than the total amount of the pressure in the second volume and the predetermined value. When the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the chromatography, the first  
20 plunger may decrease the first volume to increase the pressure of the liquid in the first volume to more than the pressure in the second volume and is prevented from decreasing the first volume sufficiently for increasing the pressure of the liquid in the first volume to more  
25 than the total amount of the pressure in the second volume and the predetermined value.

When the second plunger increases the second volume, the first plunger decreases the first volume

sufficiently for feeding the liquid from the first volume into the second volume so that the flow of the liquid discharged from the pump is maintained. The movement of at least one of the first and second plungers (that is, a relative movement between the first and second plungers) should be controlled in such a manner that a difference between a difference (in absolute value) between the increasing rate (per time) of the second volume increased by the second plunger and the decreasing rate (per time) of the volume of the first volume decreased by the first plunger and a predetermined degree is kept within an acceptable range. For keeping the flow rate of the liquid discharged from the pump desirably, it is preferable that the decreasing rate (per time) in absolute value of the first volume decreased by the first plunger is more than the increasing rate (per time) in absolute value of the second volume increased by the second plunger, and the movement of at least one of the first and second plungers (that is, the relative movement between the first and second plungers) is controlled in such a manner that a difference between a difference in absolute value between an increasing rate (per time) of the second volume increased by the second plunger and a decreasing rate (per time) of the volume of the first volume decreased by the first plunger and a desired flow rate of the liquid to be discharged from the second volume to the outlet path for the chromatography

is kept within a predetermined range.

For rapidly discharging a gaseous bubble out of the pump and securely preventing the discontinuation of the correctly maintained minimal flow rate of the liquid, it is preferable that a change rate (per time) in absolute value of the first volume with respect to a movement velocity in absolute value of the first plunger is larger than a change rate (per time) in absolute value of the second volume with respect to a movement velocity in absolute value of the second plunger. For keeping the minimal flow rate of the liquid correctly, it is preferable that the first plunger is capable of being stationary at least temporarily when the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the chromatography.

The outlet path may include a drain valve openable to discharge a gas out of the outlet path through the drain valve to fill the outlet path with the liquid when the first plunger decreases the first volume, and closable to discharge the fluid from the second volume out of the pump through the outlet path for the chromatography when the second plunger decreases the second volume. It is preferable for rapidly discharging the bubble out of the pump and securely compensating the second plunger return movement increasing the second volume that a maximum change rate in absolute value of the first volume



obtainable in accordance with (with respect to) the movement of the first plunger is larger than a maximum change rate in absolute value of the second volume obtainable in accordance with (with respect to) the movement of the second plunger, and a minimum change rate in absolute value of the first volume obtainable in accordance with (with respect to) the movement of the first plunger is smaller than the maximum change rate in absolute value of the second volume obtainable in accordance with (with respect to) the movement of the second plunger. For minimizing an adverse effect caused by the second plunger return movement increasing the second volume, that a movement velocity in absolute value of the second plunger for increasing the second volume is larger than a movement velocity in absolute value of the second plunger for decreasing the second volume to discharge the fluid from the second volume to the outlet path for the chromatography.

It is preferable for minimize the change of pressure in the second chamber on switching from the decrease of the second volume to the increase of the second chamber that the first plunger is capable of decreasing the first volume to increase a pressure in the first volume when the second plunger decreases the second volume, that is, before switching from the decrease of the second volume to the increase of the second chamber, and/or that the first plunger is capable of decreasing the first volume to pressurize

the fluid in the first volume to a pressure  
insufficient for feeding the liquid from the first  
volume into the second volume and not more than a  
desired pressure of the liquid to be discharged from  
5 the pump, when the second plunger decreases the second  
volume, that is, before switching from the decrease of  
the second volume to the increase of the second  
chamber.

A method for controlling a pump for feeding a  
10 liquid for chromatography, including, first and second  
chambers, first and second plungers forming first and  
second volumes respectively together with the first and  
second chambers and being capable of reciprocating in  
the first and second chambers respectively in such a  
15 manner that the first and second volumes are variable  
in accordance with respective movements of the first  
and second plungers, a communication path connecting  
fluidly the first and second volumes to each other, an  
inlet path communicating fluidly with the first volume,  
20 from which inlet path the liquid to be fed is capable  
of being supplied into the first volume, and an outlet  
path communicating fluidly with the second volume, by  
which outlet path the liquid to be fed is capable of  
being discharged from the second volume, comprises the  
25 steps of:

opening a drain valve in the outlet path to  
discharge a gas out of the outlet path through the  
drain valve so that the outlet path is filled with the

liquid when the first plunger decreases the first volume,

closing the drain valve when the second plunger decreases the second volume to discharge the fluid from the second volume to the outlet path for the chromatography, and

controlling at least one of the movement of the first plunger for decreasing the first volume sufficiently for feeding the liquid from the first volume into the second volume and the movement of the second plunger for increasing the second volume (that is, a relative movement between the first and second plungers) in such a manner that a difference between a difference in absolute value between an increasing rate (per time) of the second volume increased by the second plunger and a decreasing rate (per time) of the volume of the first volume decreased by the first plunger and a desired flow rate of the liquid to be discharged from the second volume to the outlet path for the chromatography is kept within a predetermined range.

Other objects, features and advantages of the invention will become apparent from the following description of the embodiments of the invention taken in conjunction with the accompanying drawings.

## Brief Description of the Several Views of the Drawings

Fig. 1 is a partially cross-sectional view showing a pump of the invention.

Fig. 2 is a diagram showing pairs of large pump flow rate ranges and small pump flow rate ranges of embodiments of the invention.

Fig. 3 includes diagrams showing a  
5 relationship among operations in a pump of the invention, time proceeding and conditions in the pump.

Fig. 4 is includes diagrams showing a relationship among operations in another pump of the invention, time proceeding and conditions in the  
10 another pump.

Fig. 5 is a partially cross-sectional view showing a liquid mixing and feeding system in which the pumps of the invention are used.

Fig. 6 is includes diagrams showing another  
15 relationship among operations in the pump, time proceeding and conditions in the pump.

Fig. 7 is a partially cross-sectional view showing a liquid mixing and feeding system in which the pumps of the invention are used.

Fig. 8 is includes diagrams showing another  
20 relationship among operations in the pump, time proceeding and conditions in the pump.

#### Detailed Description of the Invention

In an embodiment as shown in Figs. 1-3, an  
25 inlet path 10, an outlet path 11, a first chamber 12 and a second chamber 13 are formed in a pump body 1. First and second plungers 2 and 3 are supported by

slide bearings 7 and 7' respectively to be movable in the first and second chambers 12 and 13 respectively. The inlet path 10 for supplying a fluid into the first chamber 12 includes an inlet check valve 4, and a  
5 communication path communicating fluidly with the first and second chambers 12 and 13 includes a discharge check valve 5. In each of the check valves 4 and 5, a movable member is pressed against a valve seat by a spring so that a fluidal flow from a fluid tank 51 into  
10 the first chamber 12 or from the first chamber 12 into the second chamber 13 is allowed when a fluidal pressure at an upstream side of the check valve is more than a total amount of a fluidal pressure at a downstream side of the check valve and a fluidal  
15 pressure caused by the spring, and is prevented when the fluidal pressure at the upstream side of the check valve is not more than the total amount of the fluidal pressure at the downstream side of the check valve and the fluidal pressure caused by the spring. The first  
20 plunger 2 is driven linearly by a rotational motor 21 through a reduction gearbox 22 and a rotary-motion and linear motion converter 23, and the second plunger 3 is driven linearly by a rotational motor 21' through a reduction gearbox 22' and a rotary-motion and linear  
25 motion converter 23'. Seals 6 and 6' hermetically seal volumes formed respectively by a combination of the first plunger 2 and chamber 12 and a combination of the second plunger 3 and chamber 13 while the first and

second plungers 2 and 3 are movable through the seal 6 and 6' respectively. A controller 50 generates control signals for the motors 21 and 21' on the basis of an output signal of a pressure sensor 60.

5           A solvent 51 is supplied into a pump through the inlet path 10, and discharged from the outlet path 11 to be mixed with a specimen supplied by an injector 53. A solution as a mixture of the solvent 51 and the specimen proceeds through a column 54 so that the  
10 specimen is divided to components thereof for componential analysis in a detector 55. The column 54 includes silica-gel particulate through which the solution proceeds, so that a pressure loss of, for example, about 10 MPa is generated across the column  
15 54.

A large (flow rate) pump is formed by the first chamber 12 and plunger 2 and a driving mechanism therefor, and a small (flow rate) pump is formed by the second chamber 13 and plunger 3 and a driving mechanism  
20 therefor.

As shown in Fig. 2, the pump according to the invention may generate an extremely small flow rate of, for example, less than 1 mL/min or 1  $\mu$ L/min. A ratio between a maximum obtainable flow rate and a minimum  
25 obtainable flow rate in generally known pumps is 1 : 100. Therefore, the pump for the extremely small flow rate cannot generate a flow rate sufficient for filling rapidly with the fluid a fluidal line through the pump

and an analysis system at the downstream side of the pump, and for discharging rapidly gaseous bubble out of the pump. A desired flow rate is not obtainable correctly when the gaseous bubble exists in the fluidal  
5 line.

In the embodiments of the invention, the small pump generates the extremely small flow rate for analysis and the large pump generates the large flow rate for filling the fluidal line with the fluid and  
10 for discharging the gaseous bubble out of the pump before the analysis.

The obtainable minimum flow rate of the large pump is smaller than the obtainable maximum flow rate of the small pump, and the obtainable maximum flow rate  
15 of the large pump is larger than the obtainable maximum flow rate of the small pump. The flow rate is determined as a product of a cross sectional area of the plunger and a velocity of the plunger. The total flow rate along an abscissa axis in Fig. 2 is a total  
20 flow rate obtainable for a high pressure gradient pump operation in which a required maximum flow rate is from several dozen times to several hundred times of a required minimum flow rate. Therefore, a required minimum limit of resolution in flow rate of the pump is  
25 less than one tenth or hundredth of the required maximum flow rate.

In an operation of the first embodiment as shown in Fig. 3, before starting the liquid feed of the

extremely small flow rate for the analysis, a drain valve 52 is opened and the first plunger 2 reciprocates at a high frequency to generate a large flow rate of the liquid so that the gaseous bubble in the pump and the feed line is discharged therefrom and the pump and feed line are filled with the liquid. Since the large pump is arranged at the upstream side of the small pump so that the liquid supplied from the inlet path 10 flows from the large pump into the small pump to be discharged from the outlet path 11, the bubble can be easily discharged from the second chamber 2 to the outlet path 11. Further, since the liquid is supplied into each of the first and second chambers 12 and 13 at the vicinity of the seal 6, 6' and is discharged from each of the first and second chambers 12 and 13 at the vicinity of a stroke front end of the plunger 2, 3, the liquid flows without a flow stagnation through each of the first and second chambers 12 and 13. When the first plunger reciprocates to discharge the bubble from the pump and feed line, the second plunger 3 is prevented from moving.

During the liquid feed of the extremely small flow rate for the analysis, the drain valve 52 is closed, the first plunger 2 is prevented from moving and the second plunger 3 moves at a low velocity to decrease the second volume so that the liquid is discharged from the pump at the extremely small flow rate. In response to that the second plunger 3 reaches



the stroke front end thereof, the second plunger 3 returns to a stroke back end thereof at an obtainable maximum velocity and the first plunger 2 moves to decrease the first volume so that the liquid is

5 discharged from the first chamber 12 into the second chamber to keep a constant flow rate to be discharged from the second chamber 13 to the outlet path 11, that is, a total amount of a negative flow rate or volume increasing rate  $Q_2$  of the second chamber 13 and a flow

10 rate or volume decreasing rate  $Q_3$  of the first chamber 12 is kept at a desired constant flow rate  $Q_1$  to be discharged from the pump. Since the obtainable minimum flow rate of the large pump is smaller than the obtainable maximum flow rate of the small pump, the

15 flow rate or volume decreasing rate  $Q_3$  of the first chamber 12 can compensate the negative flow rate or volume increasing rate  $Q_2$  of the second chamber 13 while the desired flow rate  $Q_1$  to be discharged from the pump is maintained, when the second plunger 3

20 returns to the stroke back end thereof. Since the second plunger 3 returns to the stroke back end thereof at the obtainable maximum velocity, the obtainable minimum flow rate of the large pump can be large so that the obtainable maximum flow rate of the large pump

25 can be large.

It is preferable for increasing a pressure in the pump to a desired pressure  $P_{set}$  that the first plunger 2 moves by  $X_{ini}$  as shown Fig. 3 to decrease the

first volume to pressurize the pressure in the pump to the desired pressure. If the pressure in the pump is increased to the desired pressure  $P_{set}$  by only the movement of the second plunger 3, the stroke of the second plunger 3 needs to be large and a time period for reaching the desired pressure  $P_{set}$  needs to be long.

In response to that the first plunger 2 reaches to the vicinity of the stroke front end thereof after a plurality of times of reciprocating movements of the second plunger 13 so that a distance or remaining available stroke between a position of the first plunger 2 and the stroke front end thereof becomes insufficient for keeping the desired constant flow rate  $Q_1$  to be discharged from the pump through the return movement of the second plunger 3 to the stroke back end thereof, the first plunger 2 returns to a stroke back end thereof while the second plunger 3 moves to decrease the second chamber for keeping the desired constant flow rate  $Q_1$  to be discharged from the pump.

As shown in Fig. 4, the first plunger 2 may return to the stroke back end thereof at each forward stroke of the second plunger 3 in which stroke the second plunger 3 moves to decrease the second chamber for keeping the desired constant flow rate  $Q_1$  to be discharged from the pump. In this case, a distance between the stroke front and back ends of the first

plunger 2 may be small and the first volume may be small. When the second plunger 3 decreases the second volume to discharge the liquid out of the second volume just before the second plunger 3 returns toward the stroke back end thereof to increase the second volume, the first plunger 2 moves to decrease the first volume so that a difference in pressure between the first and second chamber is decreased to minimize a change of pressure in the second chamber.

As shown in Fig. 5, a high-pressure gradient system for changing a mixing ratio between solutions A and B gradually stepwise by adjusting a ratio between flow rates  $Q_a$  and  $Q_b$  of the solutions A and B while a total amount of the flow rates  $Q_a$  and  $Q_b$  is kept constant may be formed a pair of the pumps of the invention. The ratio between the flow rates  $Q_a$  and  $Q_b$  of the solutions A and B is changed from 1 : 99 to 99 : 1, as shown in Fig. 6. When the total amount of the flow rates  $Q_a$  and  $Q_b$  is 1  $\mu\text{L}/\text{min}$ , a correctly obtainable minimum flow rate, or minimum limit of resolution of each of the flow rates  $Q_a$  and  $Q_b$  is 10nL/min of one hundredth of 1  $\mu\text{L}/\text{min}$  is required as a correctly obtainable minimum flow rate, or minimum limit of resolution of each of the flow rates  $Q_a$  and  $Q_b$ . If the flow rate discharged from the pump is kept constant, an outlet pressure of the liquid discharged from the outlet path 11 changes in accordance with a change of the mixing ratio, because a fluidal

resistance of the column 54 changes in accordance with the change of the mixing ratio.

A relationship between the mixing ratio and the outlet pressure of the liquid obtained when the flow rate discharged from the pump is kept constant is measurable experimentally. Therefore, the change of the outlet pressure of the liquid or a desired outlet pressure of the liquid in accordance with the change of the mixing ratio necessary when the flow rate discharged from the pump is kept constant can be estimated. When an actual outlet pressure of the pump is adjusted by a feedback control at the desired outlet pressure of the liquid necessary when the flow rate discharged from the pump is kept constant, the flow rate discharged from the pump is kept correctly constant. As shown in Fig. 5, an output signal of a pressure sensor 60a or 60b corresponding to the actual outlet pressures of the pumps is input to a main controller 70 so that the pump controllers 60 and 60' controls the pumps to generate the desired outlet pressure of the liquid.

When the actual outlet pressure of the pump is lower than the desired outlet pressure of the liquid, that is, an actual total amount of the flow rates  $Q_a$  and  $Q_b$  is lower than the desired total amount of the flow rates  $Q_a$  and  $Q_b$ , feedback gains for controlling the flow rates  $Q_a$  and  $Q_b$  respectively are adjusted in accordance with the ratio between the flow

rates  $Q_a$  and  $Q_b$ . For example, when the ratio between the flow rates  $Q_a$  and  $Q_b$  is 20 : 80, the feedback gain for the flow rate  $Q_a$  is  $(20/100) \times K$  (numerical constant), and the feedback gain for the flow rate  $Q_b$  is  $(80/100) \times K$ . When the actual total amount of the flow rates  $Q_a$  and  $Q_b$  is smaller than the desired total amount of the flow rates  $Q_a$  and  $Q_b$  by 5, an ordered value for the flow rate  $Q_a$  is  $20 + (20/100) \times K \times 5$ , and an ordered value for the flow rate  $Q_b$  is  $80 + (80/100) \times K \times 5$ .

Since the outlet pressure of each of the pumps varies in accordance with a time proceeding, the pressure in the first volume of each of the pumps needs to change in accordance with the change of the outlet pressure of each of the pumps. In order to prevent the liquid from flowing from the second volume into the first volume, the movement of the first plunger 12 is controlled by the feed back control on the basis of comparison between each of the pressures measured by the sensors 60a' and 60b' and the pressure measured by the sensor 60a in such a manner that the pressure in the first volume of each of the pumps is not more than the pressure in the second volume of the each of the pumps.

As shown in Fig. 7, the check valve 4 may be replaced by a shutoff valve 58 in the inlet path 10, and the check valve 5 may be arranged in the outlet path 11 instead of the communication path. In this

embodiment, as shown in Fig. 8, the first plunger 2 does not compensate the increase of the second volume by the return stroke of the second plunger 3 toward the back stroke end thereof to keep the pressure in the outlet path 11 constant during the return stroke of the second plunger 3. Before feeding the liquid for the analysis, the first plunger 2 is positioned at the front stroke end thereof and the second plunger 3 is positioned at the back stroke end thereof while the shutoff valve 58 and the drain valve 52 are opened. Thereafter, the first plunger 2 is returned to the back stroke end thereof to take the solution 51 into the first chamber while the second plunger 3 is stationary. After the first plunger 2 reaches the back stroke end thereof, the shutoff valve 58 is closed. Subsequently, the first plunger 2 is moved toward the front stroke end thereof to decrease the first volume so that the gaseous bubble is discharged out of the pump from the drain valve 52. Before the first plunger 2 reaches the front stroke end thereof, the drain valve 52 is closed and the first plunger 2 is stopped. Subsequently, the first plunger 2 moves by the distance  $X_{ini}$  to decrease the first volume so that the liquid in the first and second volumes is pressurized to the predetermined pressure  $P_{set}$ . While the first plunger is kept stationary, the second plunger 3 moves toward the front stroke end thereof to decrease the second volume to feed the liquid at the flow rate  $Q_1$ .

The second plunger 3 may be driven to change the second volume by a piezoelectric actuator or a thermal expansion metallic actuator. The first and second chambers 12 and 13 may be arranged in respective  
5 pump bodies separated from each other and fluidly connected to each other by a communication pipe line.

It should be further understood by those skilled in the art that although the foregoing description has been made on embodiments of the  
10 invention, the invention is not limited thereto and various changes and modifications may be made without departing from the spirit of the invention and the scope of the appended claims.